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13. ABSTRACT (Maximum 200 words)  The objective of this research project was to increase the current level of understanding of the interaction between an unsteady hydrodynamic field and the chemical kinetics in a laminar diffusion flamelet. A steady counterflow diffusion flame burner has been modified to allow periodic oscillations of the input velocity. Laser diagnostics were used to quantitatively measure soot volume fraction in an unsteady propane-air counterflow diffusion flame. The instantaneous strain rate at global flame extinction for a propane-air flame has been measured as a function of steady strain and both amplitude and frequency of the unsteady component. Two component LDV was used to measure the velocities allowing determination of the true strain rate. The phase lag between velocity and strain rate was quantified. Low frequency oscillations in the reactant flow rates increased net soot production by as much as 6 times over the steady flame. At low initial strain rates, high frequency oscillations reduce the maximum soot volume fraction by as much as 90% of the steady flame soot concentration. At high initial strain rates, soot production was insensitive to high frequency oscillations.				
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**Forward**

The majority of practical combustion devices rely on turbulent diffusion flames to convert chemical energy into thermal energy, and hence into mechanical work. The US Army has a significant investment in vehicles which are powered by Diesel engines. The majority of the fuel consumed during the combustion process in these Diesel engines is diffusion controlled. It is very desirable to be able to predict physical characteristics in turbulent diffusion flames such as heat release rate, combustion efficiency, and the type and amount of pollutants formed. In turbulent diffusion flamelet theory, the turbulent flame is considered to be an ensemble of strained laminar one-dimensional flamelets, fully characterized by two parameters, the mixture fraction and the scalar dissipation rate. The laminar counterflow diffusion flame has been shown to exhibit many of the essential features of a flamelet. The structure of counterflow diffusion flames under the influence of steady strain rates have been studied for a number of years to better understand the non-equilibrium effects of finite rate chemistry. These non-equilibrium effects lead to pollutant formation such as soot and NO<sub>X</sub>. The objective of this research project was to increase the current level of understanding of the interaction between an unsteady hydrodynamic flow-field and the chemical kinetics in a laminar diffusion flamelet. An unsteady propane-air CFDF was built and the effect of unsteady strain on the overall soot production was quantified using laser based diagnostics for a range of steady strain, amplitude and frequency of the imposed unsteady oscillation. This final report details the results of this experimental effort.

**List of Appendixes, Illustrations, and Tables**

(none included)

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**Statement of Problem**

There continues to be a high level of interest in reducing soot emissions from combustors due to more strict environmental regulation of particulate emissions, and for military vehicles, the desire to decrease the vehicles' detectability. Most practical combustion processes, such as those found in Diesel engines, rely on turbulent diffusion flames to burn multi-component hydrocarbon fuels and are well known for their high soot emissions. The study of chemical processes, such as soot formation, in turbulent diffusion flames is complicated by the unsteady multi-dimensional flowfield, complex hydrocarbon chemistry, and the interaction between the flowfield and chemistry. Flamelet theory simplifies the analysis of a turbulent diffusion flame by treating the flame as an ensemble of strained, laminar, one dimensional flamelets which can be described by two variables. Counterflow diffusion flames exhibit many characteristics of flamelets. Currently, researchers assume flamelets respond in a quasi-steady manner to the unsteady strain rates in the real turbulent diffusion flame. However, the validity of this assumption has come under close scrutiny recently. There is an effort to assess the unsteady effects of the turbulent flow-field on the chemistry analytically, numerically, and experimentally.

The strain rates at flame extinction were experimentally measured in an unsteady counterflow diffusion flame as a function of initial strain rate, oscillation frequency, and amplitude of the imposed fluctuation for both strong and weak hydrocarbon flames. The axial and radial velocity components were measured with a two-component LDV system. The strain rate was determined by curve fitting the measured axial velocity profile just before the heat release zone and finding the curve fit's maximum derivative. The phase relationship between speaker deflection and velocity fluctuation was quantified. The velocity profile was measured assuming both constant and variable phase angle to quantify the effect of the phase angle dependence on spatial location in the flow field. At the phase angle corresponding to maximum velocity, the strain rate was measured at oscillation amplitudes near the extinction limit for propane/air and both diluted and undiluted methane/air flames. These measurements were extrapolated to the extinction amplitude to determine the instantaneous, unsteady, extinction strain rate. For one frequency, the strain rate was measured at four different phase angles within the velocity oscillation.

To study the local effect of unsteady strain on these flamelets, it was desirable to look at a physical quantity that is sensitive to the local environment and time scales. Soot was chosen as the indicator for two reasons. First, it is of primary interest to the US Army for reasons already stated, and second, there exists a viable technique to quantify the soot volume fraction, called Laser

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Induced Incandescence (LII). The LII technique uses a short laser pulse to heat soot particles to their vaporization temperature and collects the resulting incandescence. This incandescence can be related to the soot volume fraction with appropriate choices for pump and detection wavelengths. For quantitative soot volume fraction measurements in the unsteady CFDF, the LII signal intensity must be calibrated with another measurement technique, such as line-of-sight laser extinction. The LII signal was first calibrated in an ethylene jet diffusion flame. This flame type and fuel were chosen because there was ample published data available for comparison. With a calibrated technique, we were able to measure quantitative soot volume fractions in the unsteady counterflow diffusion flame as a function of oscillation frequency and amplitude for a number of initial strain rates. Measurements were also taken within a single oscillation at high temporal resolution to determine the transient effects of the chemistry in keeping up with the fluid mechanics.

Future efforts will be focused on obtaining simultaneous velocity and [OH] measurements using a PIV-PLIF system to better understand and quantify the transient strain rate and its effect on the chemistry. A second major thrust will be to study the physical attributes of the soot. With LII, we were able to quantitatively measure the soot volume fraction, but we were not able to say anything about the soot morphology. It is important to know if the primary particle size and the number particles per aggregate is changing due to this unsteady strain rate. We will use a phase-locked angular scattering technique to ascertain many soot morphology parameters and track them through the oscillation period. We will extend the current state of the art in point scattering measurements to a planar technique.

#### **Summary of primary results**

The primary results are divided into three groups. First, the global response of the flame to the strain rate oscillations was quantified by measuring the instantaneous strain rate at global flame extinction as a function of initial strain rate, oscillation frequency, and amplitude of the imposed fluctuation. This was done for both methane- and propane-air flames. Second, the effect of the unsteady strain on the overall soot production was quantified as a function of initial strain rate, oscillation frequency, and amplitude of the imposed fluctuation. Third, progress was made towards establishing a two-color PLIF thermometry technique to be used in these sooty environments.

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Extinction strain rates in unsteady methane- and propane-air counterflow diffusion flames were experimentally measured as a function of initial strain rate, oscillation frequency, and amplitude of the imposed fluctuation. The maximum strain rate was found to occur at a temporal phase corresponding to the maximum velocity for the diluted methane flame. However, for the propane flame, the maximum strain rate occurred when the imposed velocity fluctuation was zero and decreasing. Above an oscillation frequency of 100 Hz, the diluted methane flame was able to survive peak strain rates exceeding the steady extinction strain rate. The minimum air velocity within the oscillation for both the pure methane and propane flames was negative for all cases studied. This is most likely responsible for the flame extinction measured at low frequencies and initial strain rates. However, at high initial strain rates and forcing frequencies, peak unsteady strain rates at extinction approached, and may have actually exceeded, the steady extinction strain rate. Flow reversal was much less significant at these high initial strain rates and the flame appeared to extinguish due to the peak strain rate.

Specific conclusions from the first part of the research include:

1. The actual instantaneous peak strain rate increases linearly with speaker oscillation amplitude.
2. The phase angle of the velocity oscillation was quantified and found to be a function of the axial coordinate, which artificially increases the measured strain rate. This change was accounted for and the true instantaneous strain rates were measured. The phase angle was not a function of oscillation amplitude or initial strain rate.
3. The weaker diluted methane flame responded in a quasi-steady manner at low frequencies, but departed from quasi-steady as the frequency was increased beyond 100 Hz, where the flame was able to survive short excursions above the steady strain rate limit. This flame was not subject to flow reversal at any frequency.
4. For the stronger methane and propane flames, the minimum velocity within the oscillation at extinction was negative. This significantly distorted the flow-field and is most likely responsible for extinction at the low frequencies and low initial strain rates, as the peak strain rate was much lower than the steady extinction strain rate. The magnitude of flow reversal at the extinction amplitude decreased with increasing initial strain rate and oscillation frequency, but the propane and methane flames were always subjected to some degree of flow reversal. At the higher frequencies and initial strain rates, the peak instantaneous strain rate was approximately equal to the steady strain rate. It is not clear if initial strain rates closer to the

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steady extinction limit would permit brief excursions above the steady extinction limit for these strongly burning flames, as in the diluted methane-air flame.

5. For the methane and propane flames, peak instantaneous strain rate does not occur at the maximum velocity within the oscillation, but rather somewhere near zero fluctuation velocity with a negative slope. This indicates that the velocity and strain rate are out of phase with each other in these strongly burning flames.

In the second part of the research effort, the non-intrusive LII diagnostic technique was used to make spatially and temporally resolved measurements of the soot volume fraction in steady and unsteady counterflow diffusion flames. This research is the first study of soot formation in unsteady counterflow diffusion flames and has added to the knowledge base for using these flames as models for flamelets. This work has also furthered the use of laser induced incandescence as a diagnostic tool. The specific conclusions drawn from this part of the research effort are enumerated below.

1. Steady flame soot volume fraction measurements and the soot inception limit of  $90 \text{ s}^{-1}$  compared well with published data.
2. For the unsteady flames, the phase lag between the velocity and strain rate fluctuations was evident in the planar images of soot volume fraction at four temporal positions in the velocity oscillation. The phase lag was quantified by measuring the soot volume fraction at 20 steps within the fluctuation and was found to be approximately  $\sim 125^\circ$ .
3. Low frequency oscillations increased soot production by as much as 6 times over the steady flame.
4. At high initial strain rates, soot production was insensitive to high frequency oscillations.
5. At low initial strain rates, high frequency oscillations reduce the maximum soot volume fraction by as much as 90% of the steady flame soot concentration.
6. Reduction of soot volume fraction was an exponential function of mean velocity.
7. Striations of soot concentration were seen at low initial strain rates. The number of striations was a function of oscillation frequency and mean axial velocity. The soot particles were large enough that they had negligible diffusion velocities and were effected by the local gas velocity.

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The third part of this research project is continuing under an AASERT award and will extend the two-color OH PLIF thermometry technique for use in sooting flames. The technique has been successfully used in hydrogen- and methane -air steady counterflow diffusion flames. An eight-level model is being developed with Dr. Michael Brown at MetroLaser to model the PLIF signal.

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**List of publications and technical reports**

1. M. E. DeCroix and W. L. Roberts, "Transient Flow Field Effects on Soot Volume Fraction in Diffusion Flames," Combust. Sci. & Tech., (submitted)
2. M. E. DeCroix and W. L. Roberts, "Study of Transient Effects on the Extinction Limits of an Unsteady Counterflow Diffusion Flame," Combust. Sci. & Tech., (to appear)
3. DeCroix, M. R., Roberts, W. L., "Soot Formation in an Unsteady Counterflow Diffusion Flame," poster presented at the 27th Symposium (International) on Combustion, Boulder, CO., Aug. 98
4. M. E. DeCroix, W. L. Roberts and R. D. Gould, "Velocity Measurements in an Unsteady Counterflow Diffusion Flame using Laser Doppler Velocimetry," Experimental and Numerical Flow Visualization & Laser Anemometry Symposium, ASME-4920, Jun. 98
5. Roberts, W. L. "Soot, Temperature, OH Measurements in an Unsteady Counterflow Diffusion Flame," 1998 ARO/AFOSR Contractors Meeting, Long Beach, CA., Jun. 98
6. DeCroix, M. R., Roberts, W. L., and Gould, R. D., "Unsteady Velocity Measurements in a Counterflow Diffusion Flame using Laser Doppler Velocimetry," Eastern States Section of The Combustion Institute, New Haven Conn., Oct. 97
7. Santoianni, D. A., Cataldo, C. A., and Roberts, W. L., "Laser-Induced Fluorescence Measurements of Temperature in a Counterflow Diffusion Flame," Eastern States Section of The Combustion Institute, New Haven Conn., Oct. 97
8. DeCroix, M. R. and Roberts, W. L., "Calibration of Laser Induced Incandescence in a Counterflow Diffusion Flame," Eastern States Section of The Combustion Institute, New Haven Conn., Oct. 97
9. DeCroix, M. R. and Roberts, W. L., "Study of Soot Formation in an Unsteady Propane/Air Counterflow Diffusion Flame," Eastern States Section of The Combustion Institute, Hilton Head SC, Dec. 96
10. DeCroix, M. R. and Roberts, W. L., "Extinction Measurements for an Unsteady Propane-Air Counterflow Diffusion Flame," poster presented at the 26th Symposium (International) on Combustion, Naples, Italy, Aug 96.
11. Cataldo, C. A. and Roberts, W. L., "Two-Dimensional Temperature Images of Hydrogen-Air Counterflow Diffusion Flames," poster presented at the 26th Symposium (International) on Combustion, Naples, Italy, Aug 96.
12. Roberts, W. L. "Soot, Temperature, OH Measurements in an Unsteady Counterflow Diffusion Flame," 1996 ARO/AFOSR Contractors Meeting, Virginia Beach, VA.
13. DeCroix, M.E. and Roberts, W.L., "Extinction Measurements for a Propane/Air Counterflow Diffusion Flame in an Unsteady Flow Field," Central States Meeting of the Combustion Institute, St. Louis MO, 1996.

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**List of all participating scientific personnel**

1. William L. Roberts, Assistant Professor. Principle Investigator
2. Dawn A. Santioanni, MS. Topic: "Two Color PLIF Measurements in a Sooty Hydrocarbon-Air Diffusion Flame." Status: scheduled to defend in Dec 1998.
3. Michele R. DeCroix, Ph.D. Topic: "Soot Formation in an Unsteady Counterflow Diffusion Flame." Status: Defended Aug 1998
4. Cory A. Cataldo, MS. Topic: "Temperature Measurements Using Two Color PLIF in a Hydrogen-Air CFDF." Status: Defended 6 March 1996.

**Report of inventions**

No inventions were reported during this research project.

**Bibliography**

(none included)

**Appendices**

(none included)